

Developing a data-driven approach to *climate-proof* a regional spatial planning instrument: the Bavarian *Alpenplan*

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Keywords: *climate change adaptation, spatial planning, natural hazards, open space, nature-based solutions, green infrastructure*

Abstract

This article develops a data-driven methodological analysis for the enhancement of a regional spatial planning instrument, the *Alpenplan* in the German federal state of Bavaria, regarding adaptation to climate change and the prevention of natural hazards. The approach considers six criteria related to climate risk: water retention potential of soils, extreme flood risk, forests for protection of soil and against avalanches, avalanche risk, landslide susceptibility, and climatic compensation areas. We computed a GIS-based overlay analysis for the Bavarian Alps to determine multifunctional areas of exceptional importance for future-proofing against climate change. It is recommended that their protection level should be upgraded to *Alpenplan* Zone C. As a Nature-based Solution for climate change adaptation, the recommendations are discussed in the context of spatial planning in the Alps more widely and in other mountain areas.

Introduction

Climate change is progressing dynamically in the European Alps and will result in far-reaching changes under all possible development scenarios (Kotlarski et al. 2023). In addition to essential climate protection measures, forward-looking adaptation to climate change must be implemented, as incorporated in international agreements such as the Alpine Convention's Climate Target System (PSAC 2019) and Climate Action Plan 2.0 (PSAC). Among other things, these documents address the role of spatial planning in climate-resilient territorial development. We argue that it is not necessarily, or only, a matter of creating new planning instruments: long-established ones also need to be upgraded.

In the German federal state of Bavaria, a unique spatial planning instrument has been in place for more than 50 years, the Bavarian *Alpenplan*, which relates in numerous ways to challenges for Alpine territorial development in the face of climate change. The question arises of the contribution that the *Alpenplan*, as a regional spatial planning instrument, can make to the roadmap for climate-neutral and climate-resilient European Alps to be achieved by 2050 (PSAC 2019). The current Bavarian Climate Report 2021 (StMUV 2021) confirms that, particularly in the Alpine region, snow-melt, prolonged precipitation, and an increasing risk of heavy rainfall will raise the likelihood of climate-related hazards, such as landslides and debris flows. The report emphasizes that the best adaptation option for planning settlements and infrastructure is to avoid vulnerable areas.

The *Alpenplan* and its impact have been addressed quite extensively in the German scientific literature (Karl 1968, 1969; Hensel 1987; Goppel 2003, 2012; Speer 2008; Job et al. 2013, 2014, 2022a, 2022b; Roth 2014; Mayer et al. 2016/17; Hasslacher et al. 2018; Lintzmeyer 2018), but it is remarkable that to date

there is only one peer-reviewed journal article in English on the subject (Barker 1982). Against the backdrop of rapid climate change in the European Alps (Pröbstl-Haider & Pütz 2016), which has become very visible with recent intense flooding (e.g. in Slovenia in summer 2023), and diminishing open spaces (Job et al. 2022), here we make an English-language plea for an adapted *Alpenplan*. The safeguarding of open space is a topic of concern in the entire region of the Alps which must be taken seriously and depends on increased cross-border spatial planning cooperation and harmonization (Hasslacher et al. 2018; ARL 2022) – also in other high mountain areas worldwide (cf. Lama & Job 2014).

The aim of this paper is to help bring about an amendment of the *Alpenplan*, since ongoing climate change requires this long-established planning instrument to be *climate-proofed* (Calliari et al. 2019; Juschten et al. 2021). We propose an expansion of *Alpenplan* Zone C (the quiet zone – see Infobox) because of the increased risks of natural hazards caused by intensifying climate change in the European Alps (Schindlberger, 2019). For climate change adaptation purposes, the existing *Alpenplan* would be updated with spatial data, and we argue for the consideration of six climate-risk related criteria for pro-active natural hazard protection: water retention potential of soils, extreme flood risk, soil and avalanche protection forests, avalanche risk, landslide susceptibility, and climatic compensation areas. GIS-computed thematic maps were drawn based on hydro-geographical landscape units of the Bavarian Alps and these six criteria.

Study area and subject

The Bavarian Alps are located in the very south of Germany and border on the three Austrian federal states of Vorarlberg, Tyrol and Salzburg. The Bavarian Alps are a dynamic region that is subject to strong in-

fluences from nearby agglomerations outside the Alps (e.g. Munich, Augsburg or Salzburg). The population benefits economically from the flow of day visitors and overnight guests, as well as from the job opportunities in the Alpine Foreland located within acceptable commuting distances. This economically viable basis also favours the preservation of large parts of the traditional Alpine cultural landscape, despite ongoing changes in agricultural practices and land use (Mayer & Job 2014).

The perimeter of the *Alpenplan* provides an official delimitation of the Bavarian Alps, with a total area of 4,393.3 km² (excluding lakes). The area comprises 104 municipal territories with a total of around 526,000 inhabitants, representing a population density of 97 inhabitants / km² (data from LfStat 2022). This population density is low compared to the Bavarian and German averages (187 and 233 inhabitants / km² respectively) (Statistische Ämter des Bundes und der Länder 2022). However, in the context of the Alps as a whole, the Bavarian Alps represent a relatively densely populated area. This is also reflected in the extent of the area's infrastructure and settlement development, as shown by Job et al. (2022).

The *Alpenplan* perimeter is not congruent with the Alpine Convention perimeter, which is greater, covering a larger area in Bavaria / Germany while also including parts of the Alpine Foreland. The Alpine Convention perimeter is, however, congruent with the 13 southernmost Bavarian districts (*Landkreise* or *Kreisfreie Städte*), from Lindau (Bodensee) in the west to Berchtesgadener Land in the east. Of these 13 districts, official German regional statistics (BBSR 2023) classify six as *sparsely populated, rural districts*, four as *rural districts with agglomeration trends* and three as *urban districts*.

But how and why was the *Alpenplan* adopted? From the late 1950s onwards, the number of ski areas in the Bavarian Alps rose very quickly, which was massively criticized by environmentalists and the German Alpine Club (DAV). In response, and in part because of the absence of data at that time, Dr. Helmut Karl of the Bavarian State Agency for Nature Conservation presented a large-scale plan of the Bavarian Alps, based on his own cartographic fieldwork and aerial photographs (Karl 1968). In this plan, he differentiated three zones, according to the degree of infrastructure development that already existed. Underlying parameters for the designations included the landscape ecology and the potential danger from natural hazards. Recognizing that individual assessments could not protect the Bavarian Alps from the rapid expansion of mass tourism infrastructure, the basic idea of the *Alpenplan* was to coordinate transport infrastructure spatially as a key function for territorial development (Karl 1969; Job et al. 2013). Based on Karl's draft, the *Alpenplan* came into force in 1972 as a sub-section, *Recreational Landscape Alps*, of the Bavarian State Development Programme (*Landesentwicklungsprogramm*, LEP) (Speer 2008).



Figure 1 – Example of a near-natural landscape in Zone C: view, from the south, of lake Königssee and its surroundings, in Berchtesgaden National Park. © Meyer 2021



Figure 2 – Example of a fairly densely populated peri-alpine area in Zones A and B: view, from the south, of lake Tegernsee and its surroundings. © Meyer 2019

The zoning of the Bavarian Alps according to three intensity levels of transport infrastructure was a far-sighted innovation, especially in relation to its Zone C (the least developed zone), for at the time both environmental protection policies and orientation towards landscape-based recreation were in their infancy (Goppel 2003). Karl's innovative work eventually helped to enhance the field of nature conservation and formal systems of protected areas (Bender et al. 2017; Hedden-Dunkhorst 2017). As the *Alpenplan* is part of the LEP, and as stated by the Bavarian State Planning Act (BayLplG Art. 3), the *Alpenplan's* objectives in spatially significant plans and projects (e.g. as concerning municipal land use) are legally binding and must be followed by all public bodies concerned (Job et al. 2017). According to Goppel (2012), the long-standing reliability of the *Alpenplan*, and the fact that its spatial scope has hardly changed over the years, is mainly due to its clear geographical delimitation, the forward-looking steering concept, and the unambiguous and legally binding nature of it as a spatial planning instrument. It has prevented the Bavarian Alps

from over-development for tourism purposes and, at the same time, has considerably extended the protection of ecologically sensitive areas, but without preventing tourism from being economically important in the region (Job & Metzler 2005; Job et al. 2014; Mayer & Steiger 2013).

The zoning structure of the *Alpenplan* has been largely constant ever since 1972, although in the LEP 2019/2020, the share of Zone C grew slightly because of the reintegration of the Riedberger Horn with two neighbouring peaks in the Oberallgäu region. Based on a political decision to allow the construction of new ski lifts, the area around Riedberger Horn was initially excluded from Zone C in early 2018, and the inclusion of the other two peaks was meant as political compensation. Following the formation of a new Bavarian federal state government in 2018, this political decision was revoked in 2019, but the two *compensatory* peaks remained in the restored *Alpenplan* Zone C. An enlargement of Zone C had happened once before, when minor adjustments were made following the severe avalanche winter of 1998/1999: in the LEP of 2003, 12 small areas were incorporated into Zone C (Job & Meyer 2022b).

The *Alpenplan* is the instrument with the greatest continuity in the Bavarian State Development Programme (LEP). Job et al. (2017) documented the effective impact of Zone C by showcasing how the *Alpenplan* status, among other factors, resulted in 19 unrealized (ski) tourism projects (and the development of the infrastructure that would have been necessary) in sensitive areas. Moreover, the system of officially protected areas (comprising protected area categories such as e.g. national park or nature reserves) overlaps with the *Alpenplan*. Although it is not a sectoral instrument for nature conservation per se, it has considerable influence on open spaces in the Bavarian Alps. In fact, the *Alpenplan* provides an additional 15.2% of open spaces – that is, areas that are protected only by their Zone C status and not by official protected area designations (Job et al. 2014).

Conceptual background

The proposed approach for the enhancement of the *Alpenplan* in the face of climate change is linked to two central concepts discussed in the literature: the integration of Nature-based Solutions in planning and the consideration of multiple (overlapping) spatial functions of Green Infrastructure (GI multifunctionality). According to Cohen-Shacham et al. (2019), Nature-based Solutions complement existing (conservation/planning) principles by being more extensive and ambitious with regard to social and economic challenges. They go beyond conservation, acting as tool for environmental considerations to become mainstream in policy and practice (Cohen-Shacham et al. 2019: 26). They are thus becoming increasingly important in the context of climate change

adaptation (Lafortezza et al. 2018) by increasing the adaptive capacities of spatial planning (Kruse & Pütz 2014). Technical protection measures are often poor solutions as stand-alone measures to reduce disaster risk, because they may be limited by material wear and tear, constraints on financial resources, or aesthetic values. Protective forests in particular, then, are considered key elements in integrated risk management strategies, such as efficient Forest-based Solutions for Ecosystem-based Disaster Risk Reduction (Teich et al. 2022: 1). This is especially true when the planning applies to large areas, as in the present case, which covers the entire Bavarian Alps.

Multifunctionality is a central feature to be considered in spatial planning for open spaces and GI, combining different planning principles for safeguarding unbuilt areas (Meyer et al. 2022). In the literature, there is a growing interest in the development of specific tools for determining multifunctional GI elements, including ecosystem services as well as their connections in regional GI networks (see e.g. Goodspeed et al. 2022; Arcidiacono et al. 2016; Wang et al. 2021; Simion et al. 2023). Multifunctional GI needs to be defined very clearly if it is to be exploited effectively as a tool for delivering climate change adaptation (Sussams et al. 2015). This article therefore builds on six clearly definable input criteria in the field of climate change adaptation and prevention of natural hazards to determine those areas in the Bavarian Alps with a high level of GI multifunctionality and exposure to climate risk. These areas could then become intervention priorities for spatial planning in order to enhance the region's climate resilience.

As the approach to adapting the *Alpenplan* presented here does not dispute the plan's conceptual logic but merely the spatial distribution of zones, this can still be referred to as a form of Euclidian Zoning. There is no transnationally established definition of zoning, but the terms Euclidean or Exclusionary Zoning¹ are frequently used in an English-speaking context to conceptualize the spatial separation of land use types. Zoning represents a long-standing, widely-used concept (Bäing & Webb 2020), which nowadays can be challenged from various perspectives, especially in urban planning studies (see e.g. Hall 2006). Although criticized as a *top-down* planning approach, zoning should not be discarded as an outdated *relic*. This is demonstrated by the continuous and widespread societal and political appreciation of the *Alpenplan* in Bavaria, across most political parties and administrations, and by many NGOs.

Methods

Since this research article is intended to provide concrete advice for Bavarian spatial planning policy,

¹ See <https://www.planetizen.com/definition/euclidean-zoning> (15.11.2023)

the specific climate risks identified in the official Bavarian Climate Report (StMUV 2021) were taken as a starting point. These include landslides, slope breaks, floods, avalanches and heat events. Since an area-based analysis was aimed for, the entire official geodata base available from public authorities in Bavaria² was first examined for suitable datasets. A dataset was selected as an input criterion if it was available for the entire study area, *and* represents either (a) areas of climate-related (natural) risks that may increase in frequency or spatial extent as a result of climate change, or (b) area-based functions of Green Infrastructure that contribute to the prevention or mitigation of climate-related (natural) risks.

The logic of the proposal is characterized by the *Alpenplan* concept of deliberately keeping endangered areas free of (further) development, as well as including areas with protective functions (e.g., forest for protection of soil or against avalanches). Both types of area need to be safeguarded by regional spatial planning designations in order to increase the resilience of Alpine territories.

After the initial selection of the input criteria, their relevance for climate change adaptation and natural hazard prevention was validated using scientific literature in the fields of slope stability (Chiarle et al. 2021; Wood et al. 2015; Gariano & Guzzetti 2016), protective forests (Teich et al. 2022; Lingua et al. 2020), soil functions and flood retention (Schmidt et al. 2001; Markart et al. 2021; Vrščaj 2019), avalanches (Strapazzon et al. 2021; Zgheib et al. 2022), as well as cold air flows from open spaces into settlements (Sung et al. 2021).

The workflow for the analysis is summarized in Figure 3, with Table 1 providing a detailed overview of the input datasets used, with references and details on the selected sub-features of shapefiles. The workflow is composed of two methodological strands, which are then combined: an overlay analysis of the selected input criteria and the delimitation of Analytical Landscape Units (ALU). All analytical steps were conducted in ArcGIS Pro 3.1.1 using arcpy geoprocessing modules and functions. All area-based calculations were conducted in ETRS89 / UTM zone 32N (EPSG:25832), to comply with the uniform spatial reference system for the use of geodata in Germany and Europe.

A total of 4,544 ALUs (see Figure 4a) were produced by intersecting the existing *Alpenplan* Zones with the EU-Hydro hydrological basins (to include the topographic landscape structure) and removing a selection of features from the Digital Landscape Model (ATKIS-Basis DLM), as shown in Figure 3 and Table 1. These excluded features comprised a selection of settlement areas (≥ 1 ha), roads, major farm or forest tracks, railways and water bodies. For all line features representing transport infrastructure, the

buffering methodology from IÖR-Monitor³ was applied (and buffer sizes were then doubled) to generate polygon features that are excluded from ALUs. For water bodies, only major features presented as polygons in ATKIS-Basis DLM were considered. Since the current Zone C of the *Alpenplan* is not the focus of the analytical approach of this article (but rather the potential upgrading of certain areas to Zone C), Zone C areas were also removed from the ALUs. Due to the different extents of the cartographic generalization of the features that are included or excluded, topological errors can occur at the margins of features. These had to be cleared up by excluding small *sliver* polygons of less than 1 ha from the ALUs generated.

³ The operators of the IOER-Monitor developed a methodology to transform linear objects from the ATKIS Basis-DLM into polygons by assigning differentiated buffer sizes according to the different tabular attributes of the line features (IÖR 2023).

Infobox

Objective, functionality and impact of the Alpenplan

The Alpenplan is based on the idea that transport infrastructure development plays a key role in overall territorial development because of its indirect effects on settlement and tourism development (Meyer et al. 2021). The Alpenplan regulates the development of infrastructure projects in the Bavarian Alps such as ski lifts and cable cars (in so far as they serve public transport), ski and toboggan runs, public and private roads and trails (with the exception of hiking trails), and airfields. Without easy access (e.g. roads, car parks, cable cars), classical tourism tends to be of low intensity in mountain areas (Schamel & Job 2017). The Alpenplan creates an area-wide and fundamental solution that is not dependent on individual case decisions; furthermore, it takes into account the various demands of tourism, the local economy and nature conservation in equal measure (Job et al. 2017). The main mechanism of the Alpenplan is the zoning of the Bavarian Alps as a whole (4,393.3 km² excluding lakes, affecting 104 municipal territories), based on how land is used, how sensitive the Alpine environment is, and what development might be suitable in the future. The zoning comprises:

- Zone A or *development zone* (35 % of the Bavarian Alps), which includes all large settlements and most areas with existing intensive land use in the valley areas.
- Zone B or *buffer zone* (22%), where projects are allowed only after detailed examination and on condition that they do not conflict with priority spatial planning requirements (especially nature conservation).
- Zone C or *quiet zone* (43%), which is designed as a generally protected zone: all transport infrastructure projects (except tracks necessary for traditional agriculture and forestry) are explicitly prohibited. Implicitly, therefore, only non-intensive, landscape-based recreational uses are permitted. Forest tracks and dirt roads for the management of traditional cultural landscapes (e.g., to reach Alpine pastures) are the only infrastructures allowed (Mayer et al. 2016/17).

² Geoportal Bayern: <https://geoportal.bayern.de/geoportalbayern/seiten/dienste> (17.08.2023)

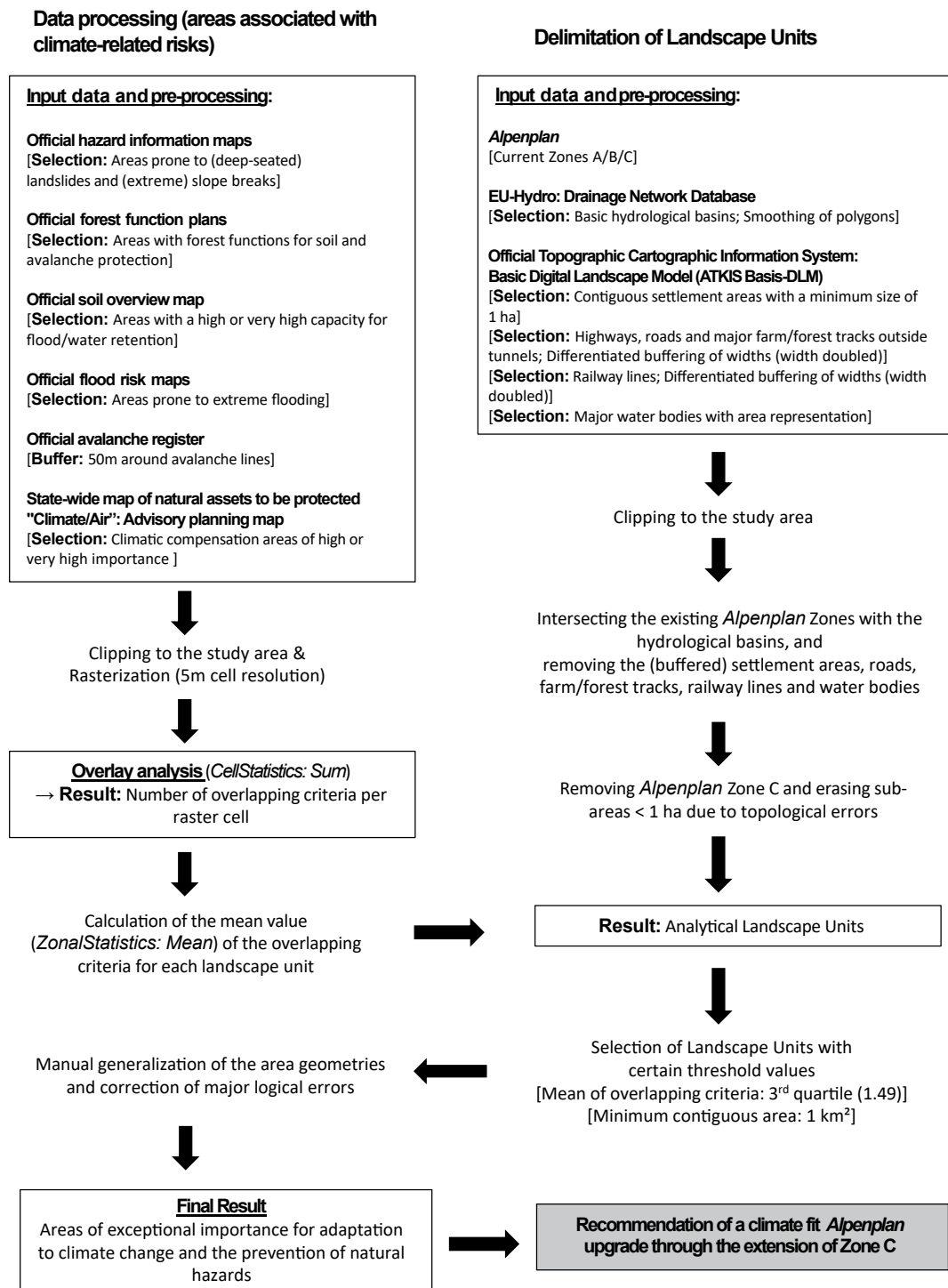


Figure 3 – Analysis workflow. Source: Authors' figure

For the overlay analysis, relevant components of the source datasets were first selected (e.g. areas prone to (deep-seated) landslides and (extreme) slope breaks), or buffered (50 m buffer around officially documented avalanche lines). The vector shapefiles were then converted into raster datasets with 5 m-cell resolution for analysis and cropped to the study area (see Figure 5 for the six data sets). Figure 4b shows the intermediary results of the overlay analysis – i.e., the number of overlapping input criteria per raster cell,

where a maximum value of 5 and a mean value of 1.31 was observed throughout the 178,130,777 raster cells for the total study area. The overlay analysis was created using the Cell Statistics (Spatial Analyst) tool, returning the *sum* value on the location of each raster cell. The *mean* value was then identified for each ALU, using the Zonal Statistics (Spatial Analyst) tool.

Subsequently a selection of ALUs with certain threshold values had to be made, taking into account the mean of overlapping criteria and the minimum

Table 1 – Overview of the data sources.

dataset	last updated	source	selection	used for	comments on processing
Alpenplan Zones A/B/C	2019	Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie	All three layers selected	Delimitation of ALUs	-
EU-Hydro – River Network Database	2020 (version 1.3)	European Environment Agency (EEA) under the framework of the Copernicus programme	Basic hydrological basins for Danube watershed	Delimitation of ALUs	Smoothing of polygon borders for vector processing
Official Topographic Cartographic Information System: Basic Digital Landscape Model (ATKIS Basis DLM)	2023	Bayerische Vermessungsverwaltung/ Landesamt für Digitalisierung, Breitband und Vermessung (open data)	sie02_f.shp (>= 1 ha) gew01_f.shp ver01_l.shp ver02_l.shp ("OBJART_TXT = 'AX_Fahrwegachse' And FKT = '5211'") ver03_l.shp ("OBJART_TXT = 'AX_Bahnstrecke'") ver06_l.shp ("BWF = '1870'")	Delimitation of ALUs	Differentiated buffering of ATKIS Basis-DLM line features, as proposed by IÖR-Monitor (IÖR 2023); doubling of the buffer size for this analysis; extracting tunnels from line features
Official hazard information maps (Amtliche Gefahrenhinweiskarten)	2014	Bayerisches Landesamt für Umwelt	GHK_tief_rutsch.shp GHK_rutschanf.shp GHK_hang_extrem.shp GHK_hang.shp	Input criterion: Official hazard information maps	Merging of selected hazard areas
Official forest function plans (Amtliche Waldfunktionsskartierung)	2021	Bayerische Landesanstalt für Wald und Forstwirtschaft	Bodenschutzwald.shp Lawinenschutzwald.shp	Input criterion: Official forest function plans	Merging of selected forest functions
Official avalanche register (Lawinenkataster)	2020	Bayerisches Landesamt für Umwelt	lawinenstriche_epsg25832.shp	Input criterion: Official avalanche register	50m buffer around avalanche lines
State-wide map of natural assets to be protected Climate/Air: Advisory planning map (Landesweite Schutzgutkarte Klima/Luft: Planungshinweiskarte)	2021	Bayerisches Landesamt für Umwelt	Ausgleichsraum_r10.shp ("KL_AR_2 = 1 or KL_AR_2 = 2")	Input criterion: State-wide map of natural assets to be protected Climate/Air: Advisory planning map	Merging of climatic compensation areas of high and very high importance
Official flood risk maps - Areas prone to extreme flooding (Hochwassergefahrenflächen HQextrem)	2013	Bayerisches Landesamt für Umwelt	hwdfHQextrem_23_02_2023.shp	Input criterion: Official flood risk maps	-
Official soil overview map (Übersichtsbodenkarte ÜBK25 – Wasserrückhaltevermögen bei Starkniederschlägen)	2020	Bayerisches Landesamt für Umwelt	UEBK25_Wasserretention_alp.shp ("RETENTION1 ≥ 4")	Input criterion: Official soil overview map	Merging of areas with high and very high capacity for flood/water retention

contiguous area size of the polygons. These thresholds cannot be determined on a completely objective basis: they depend to some extent on the judgement of experts. We chose to include ALUs that feature a mean value of 1.49 (representing the 3rd quartile of all ALUs) or higher. We also decided to include only ALUs with a minimum contiguous size of 1 km² as being relevant for zoning in supra-local spatial planning. Before presenting the final results, some polygon geometries were manually generalized (e.g., in proximity to settlement areas) and some logical errors (affecting the proposed future zoning of *Alpenplan* Zone C) were manually corrected. Since they are the results of a partly automated GIS-model, not all recommended extensions of Zone C comply with the current land use characteristics. To highlight these inconsistencies, potential land use conflicts generated by the proposal (e.g., Alpine ski runs, or other intensive tourism and building infrastructure) were marked on three detailed large-scale maps (see Supplementary Material No. 1–3).

Results

The results show areas of exceptional relevance for adaptation to climate change and the prevention of natural hazards in the Bavarian Alps. These are currently inside *Alpenplan* Zones A or B, and we recommend them as an analytical starting point for an upgrade to Zone C. The areas are visualized in Figure 6, which also illustrates the current zoning structure and extent of the *Alpenplan*. Regarding their spatial distribution, it is apparent that many of these are adjacent to the existing Zone C. The total area identified for re-zoning covers 713.12 km², with individual sub-areas measuring an average of 5.19 km². The largest contiguous sub-area is a 106.30 km², near-natural landscape area between the Isarwinkel and lake Kochelsee, near the Kocheler Berge, Jachenau valley and Benediktenwand ridge. If these areas were added to Zone C, the zone would be increased by 39.4%. Zones A and B would consequently decrease by 254.10 km² (–16.3%)

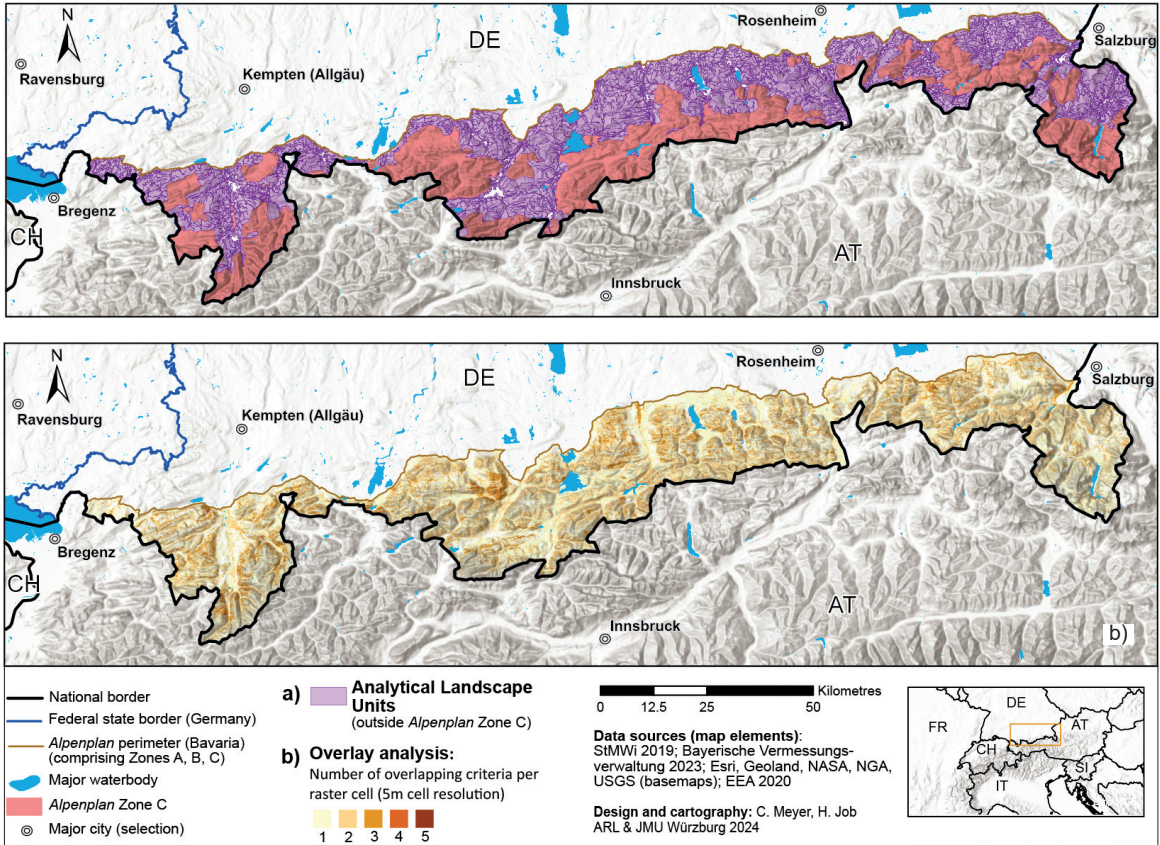


Figure 4 – (a) Visualization of the Analytical Landscape Units (ALUs); (b) the results of the overlay analysis (the brown line shows the Alpenplan perimeter, comprising all Zones A/B/C, and outlining the northern limit of the Alpenplan). Source: Authors’ figure

and 483.01 km² (–49.6%) respectively. The new ratio between the *Alpenplan* zones would then be as follows: Zone A 29.7%, Zone B 11.1%, Zone C 59.2%.

From a nature conservation perspective, 19.2% of the areas designated for upgrading would overlap with strictly protected areas (nature conservation areas, national park, Natura 2000 areas listed under the Birds Habitats Directives), compared to a significantly higher overlap of 70.2% in the current extent of Zone C. This underlines the urgent need for additional safeguarding mechanisms by spatial planning for the designated areas. Differences in terms of elevation also exist between Zone C in its current form (mean elevation 1,388 m a.s.l.) and its potential extension areas (mean elevation 1,099 m a.s.l.).⁴ This, too, is important because up to now strictly protected areas tend to be far fewer in mid-altitude areas or even Alpine valleys, thus failing to ensure ecological connectivity (ALPARC 2023).

Because of the expected land use conflicts mentioned earlier, and due to methodological limitations, not all designated areas can be included in the planning in precisely the same way. To enable a much closer examination of the identified areas, three detailed

large-scale maps (scale 1:250,000) of the eastern, central and western parts of the study area are provided in the supplementary material (No. 1–3). These maps include the (manually digitized) areas at risk of erosion (*Erosionsgefährdete Bereiche*) from the original version of the *Alpenplan* (LEP 1972, available from StMLU 1980), as they are thematically related to this analysis. They overlap the current Zone C by 20.7%. Inclusion of the areas at risk of erosion recommended for upgrading to Zone C results in an even higher overlap, of 28.2%. These detailed maps are intended to provide planning stakeholders with a basis for assessment, as they cover the same map sheets as those in the official *Alpenplan*.

Discussion

Methodological reflections

The approach provides a data-driven and replicable method for identifying areas of high relevance for adaptation to climate risks at supra-local landscape scale. The selection of criteria and data, however, brings both advantages and disadvantages. The use of official geographic information from state authorities suggests that the results could be more widely accepted by state planning stakeholders. However, the availability of reliable geodata limits the analytical scope, because not all potentially relevant climate-related risks can be

⁴ The analysis of the mean elevations was conducted using the EU-DEM v1.1 dataset at 25 m resolution (EEA 2016).

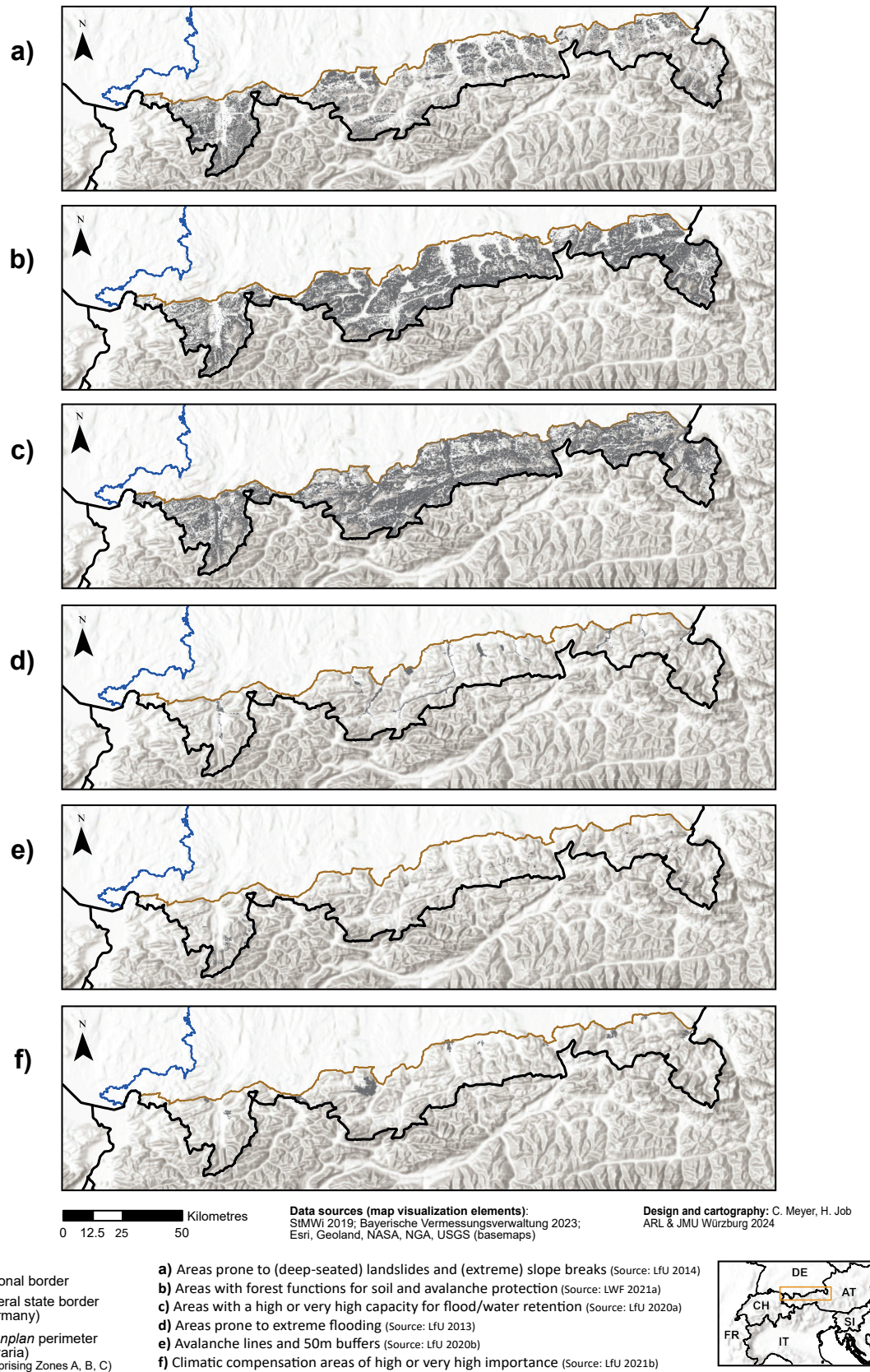


Figure 5 – Visualization of the spatial distribution of the six input criteria (a–f) (the brown line shows the Alpenplan perimeter, comprising all Zones A/B/C, and outlining the northern limit of the Alpenplan). Source: Authors' figure

included. For example, there is no specific geoinformation on debris flow hazards that covers the entire Bavarian Alpine region. And although information on

rockfall risks is also available within the framework of the official hazard maps, this was not included. This is because climate change triggers more complex pro-

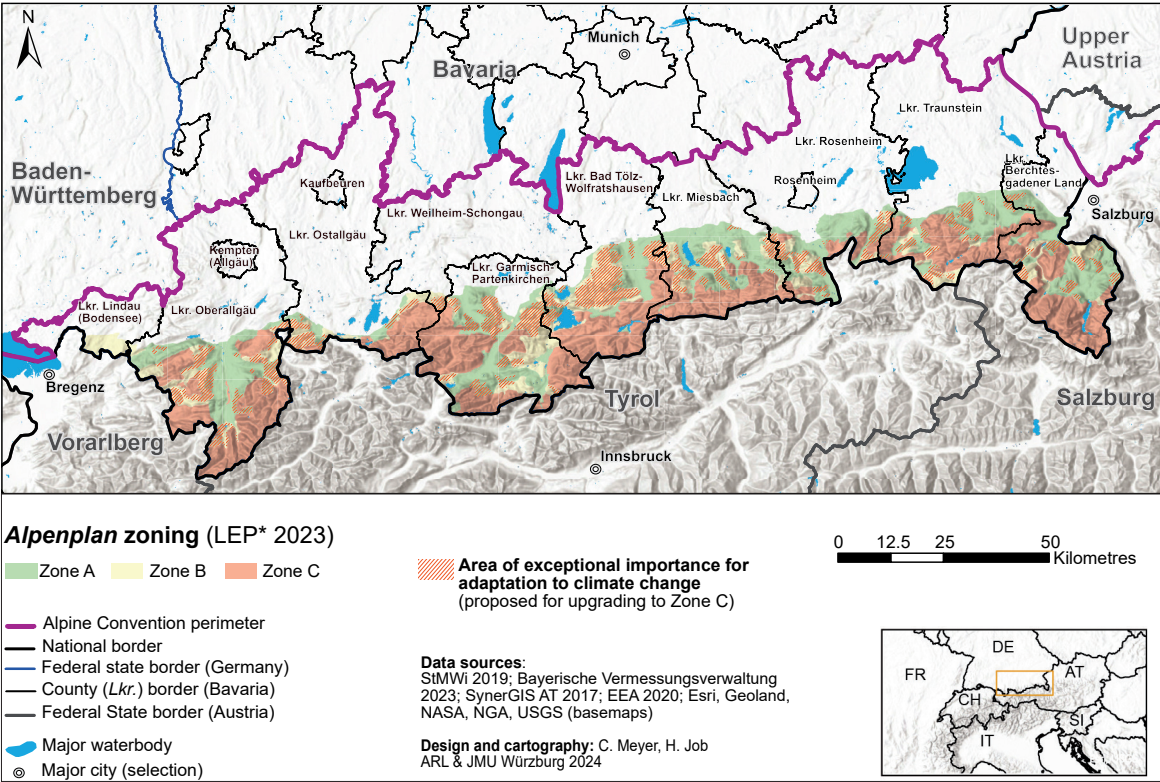


Figure 6 – Current extent and zoning of the Alpenplan, and proposed areas for upgrading to Zone C (* LEP = Landesentwicklungsprogramm Bayern). Source: Authors' figure

cesses and interactions through thawing of permafrost in mountain areas – a field that is currently being intensively studied by geoscientists (e.g. Viani et al. 2020; Knoflach et al. 2021) and which therefore could not be adequately considered in this article.

Where the methodological approach presented here is concerned, it should be mentioned that it shows a certain dependency on the selected threshold values regarding the area size and the average number of overlapping criteria measured in an ALU. The raster-based calculation is also influenced by the raster resolution. The 5-m resolution selected should ensure that the surface contours of the input features are preserved while keeping the calculation effort within reasonable limits. It should also be noted that the analysis, although designed with multifunctionality in mind, covers only part of the (potential) multifunctionality of open spaces – i.e., it focuses strongly on natural hazard risks. The future development of geodata-based tools to support planning could include other criteria relevant for open spaces (e.g. regarding outdoor recreation or landscape ecology) and development (settlements and infrastructure).

Implementation in spatial planning

Due to the area's large extent (the entire Bavarian Alps) and the the lack of knowledge about how anthropogenically driven climate change will develop, uncertainty remains as a difficult framework condition for spatial planning in general (cf. Campbell 2016).

With this article, we therefore propose a *no-regret* approach (Greiving 2018; Hallegatte 2009) that compensates for uncertainties and knowledge gaps by designating large areas as potentially being most affected by climate-related hazards. As a Nature-based Solution, the proposed adaptation of the *Alpenplan* is also a cost-effective alternative to the construction of technical structures for the protection of settlements and infrastructure. At the same time, this approach preserves the unique cultural landscape. Moreover, the approach would include in Zone C areas that are lower in elevation than the current average for the zone. This is relevant because in the European Alps most near-natural open spaces are found at higher altitudes (above 1,500 m a.s.l.) (Job et al. 2022), representing a severe weakness of Alpine GI networks.

The overlap of only 19.2% of the areas identified for intervention with strictly protected areas (nature conservation areas, national park, Natura 2000 areas listed under the Birds and Habitats Directives) suggests that the recommended adaptation would not create spatial redundancies with the existing system of protected areas in the Bavarian Alps. The different regulatory status of the *Alpenplan* (which concerns transport infrastructure and thus building development) and of protected areas (with an influence on land use and habitat protection for particular species) should again be pointed out. The *Alpenplan* specifically addresses the exposure of buildings and technical infrastructure to natural hazards. This is particularly relevant in view

of the fact that the official information maps for risks of slope failure in Bavaria / Germany (LfU 2020), in contrast to many other Alpine regions (Schindelegger 2019), do not have a binding effect. They merely have to be taken into account and weighed up in the land-use planning process of municipalities, therefore creating a rather weak institutional context for adaptation to increasing climate-related hazards.

That Bavaria can learn from other Alpine regions is also evident in the availability of spatially precise geodata that is relevant to planning. Here, for example, it is worth looking at the neighbouring Austrian federal state of Salzburg, where a comprehensive area-wide soil function assessment is available, with the sub-functions of habitat, site function, soil fertility, runoff regulation and filter function (Land Salzburg, Abteilung Lebensgrundlagen und Energie 2014). Comparing spatial planning approaches across the entire European Alps, Kruse & Pütz (2014) suggest enhancing adaptive capacities by improving the knowledge base for spatial planning, and by making climate adaptation mainstream within the entire institutional framework. Schindelegger et al. (2022) have shown that many Alpine regions have made important first steps towards climate-resilient spatial planning, but major implementation gaps still persist. Their transnational research shows that Alpine regions and municipalities are increasingly using existing planning instruments to safeguard climate services and to adapt urban development in order to deal with the impacts of climate change.

Conclusion

We argue for the significant expansion of Zone C, to almost 60% of the area covered by the *Alpenplan* (current share of Zone C: 43%). While the GIS data-driven, evidence-based approach presented here could provide an important technical impetus, it cannot replace a formal planning process. Spatial planning needs to define the designated areas precisely, taking into account current land use and settlement structure in more detail. Municipalities' existing major planning provisions should also be taken into consideration, in accordance with the Mutual Feedback Principle (*Gegenstromprinzip*) anchored in the German spatial planning system, which promotes vertical cooperation and coordination between the different planning levels (Kümper 2018). This is particularly relevant, because municipalities can be expected to voice some degree of opposition to strict planning provisions that come from the supra-local level and limit their own planning decisions and development options. At the same time, securing public acceptance at municipal level is necessary for the future development of the *Alpenplan*. The fact that the topic of climate adaptation is already gaining importance in Bavarian state and regional planning is also shown by the introduction of priority and reserved areas (*Vorrang- und Vorbehaltsgebiete*) for

adaptation to climate change in the latest version of the State Development Programme (LEP; Bayerische Staatsregierung 2023). But, since these areas were only introduced as an optional instrument, it is questionable whether corresponding plans will be implemented in all 18 Bavarian planning regions. In the three planning regions covering Alpine areas, however, their implementation will be of particular importance.

Adjustments to the zoning in LEP 2003 due to damaging avalanche events in 1998/1999 led to a small-scale update of the *Alpenplan*. In contrast to this *reactive* measure, the proposed approach represents large-scale *proactive* adaptation – in the sense of a *no-regret* strategy. In the course of *adaptive spatial governance* (Birkmann et al. 2012), it is important to weigh up the relative importance of possible incremental or long-term strategic approaches to updating spatial planning instruments. Due to its large-scale and long-term orientation, the *Alpenplan* is certainly a special case: our arguments cannot necessarily be applied to regional and municipal planning issues everywhere. Through climate-resilient enhancement and by taking into account multifunctional Green Infrastructure and emphasizing the importance of Nature-based Solutions that also support Nature-based climate protection measures, the *Alpenplan* could take on a pioneering role for future-oriented Alpine territorial development.

Other desiderata regarding the overall Alpine arc and other mountain areas of Europe and on a global scale include, firstly, establishing a standardized management system for open spaces in mountain regions at (trans-)national, regional and local scales. Secondly, deriving *Alpenplan* Zone C-like designated areas and pro-actively safeguarding them and their ecosystem services, especially soil functions. This should include climate-resilient planning specifications as well as defining more strictly protected areas, specifically in the mid-altitude areas and valleys (under 1,000 m a.s.l. – ALPARC 2023), in order to implement the recently set 30 x 30 goal of the Convention on Biological Diversity, which will also require the consistent integration of *other effective area-based conservation measures* in spatial planning (Cook 2024).

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Supplementary material

- No. 1 – <https://dx.doi.org/10.1553/eco.mont-16-2S1>
Detailed large-scale map (1:150.000) – western part (1/3)
- No. 2 – <https://dx.doi.org/10.1553/eco.mont-16-2S2>
Detailed large-scale map (1:150.000) – central part (2/3)
- No. 3 – <https://dx.doi.org/10.1553/eco.mont-16-2S3>
Detailed large-scale map (1:150.000) – eastern part (3/3)

* LEP = Landesentwicklungsprogramm Bayern 2023 / Bavarian State Development Programme, 2023 edition

** LEP 1972 = Urfassung Landesentwicklungsprogramm Bayern 1972 / Original edition of the Bavarian State Development Programme, 2023) (available from StMLU 1980)

*** Area within the *Alpenplan* perimeter strictly protected by nature conservation (Bavaria): nature conservation areas, national park, Natura 2000 areas listed under the Birds Directive and the Habitats Directive / Naturschutzfachlich streng geschützte Fläche innerhalb der Alpenplan Abgrenzung (Bayern): Naturschutzgebiete, Nationalpark, Natura 2000 Gebiete (FFH-, Vogelschutzgebiete)

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